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CLASSIFICATION OF PLASTIC AND ITS BIODEGRADATION BY MICROORGANISMS#

Christian Venisha V.[1], Makwana Sonal K.[1], Mishra Amita Y.[1], Rathod Zalak R.[1], Saraf Meenu S.[1], and Thakkar Aarti V.[2]*

Abstract

General term used for high molecular weight polymer is "Plastic". They are light weighted, durable, corrosion resistant materials, strong, inexpensive and the uncontrolled use of plastic has led to various environmental and health problems. Scientists have reported many adverse effects of the plastic in the human health and environment. Plastic causes because of increase in plastic waste disposal and burning of plastic waste causes air pollution due to the release of CO_2 and dioxins. Interest is growing for using microorganisms effectively for biodegradation of synthetic polymers. Biodegradation of plastic is a slow process but refers to change in physical and chemical properties of polymer induced by biological agents such as Bacteria and Fungi. Different strains degrade different types of plastic.

Keywords: Biodegradation, Plastic, Bacteria, Fungi.

#General Article

[1]Department of Microbiology and Biotechnology, University School of Science, Gujarat University, Ahmedabad- 380009, Gujarat, India, [2]Department of Microbiology, President Science College, Ahmedabad-380061, Gujarat, India.
venishachristian.vc@gmail.com

Introduction

Plastics are polymers used in a wide variety of industries and commerce. They were developed as strong, lightweight, durable and bio-inert materials and have been applied to a wide range of commodities. They are used in almost all the fields ranging from sophisticated articles such as prosthetic hips and knee joints to disposable food utensils. Approximately 30% of the plastics are used worldwide for packaging applications such as food, pharmaceuticals, cosmetics, detergents and chemicals (Shah, 2007). Plastics replaced many natural materials such as metals, woods and gravel. Due to the growth in residues that pollute the environment, the use of synthetic polymers has posed great concern. Cangemi et al., (2008) opined that new uses of plastics are on the increase because new and numerous applications are frequently emerging. The enormous production and utilization of polymers led to their accumulation in the environment after use. Plastics are not easily degraded by microorganisms, and thus have become a serious source of pollution affecting both flora and fauna (Arutchelvi et al., 2008).

Recalcitrant nature of plastic is due to its high molecular weight, complex threedimensional structure, and hydrophobic nature, all of them hampers its availability to microorganisms (Hadad et al., 2005). Plastics include polythene, propylene, polystyrene, polyurethane, nylon etc. Polyethylene either LDPE (low density polyethylene) or HDPE (high density polyethylene) is a thermoplastic polymer made by monomers of ethylene, used mostly as thin films and packaging sheets (Kumar et al., 2013). Plastics are used abundantly because of their stability and durability. They are different varieties of plastic such as polyethylene (PE), Poly Ethylene Terephthalate (PET), Nylons, Poly-Propylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC), and Polyurethane (PUR) (Strong, 2006). The use of plastics has transformed our life in many ways.

In fact, dioxins cause serious problems in the human endocrine hormone activity, thus becoming a major concern for the human health (Pilz et al., 2010). Dioxins also cause very serious soil pollution, causing a great concern for scientific community worldwide. Phthalates and bisphenol A are closely related in thyroid causing dysfunction in humans. The burning of polyethylene, polyurethane, polyvinyl chloride and polystyrene produces toxic irritant products that lead to immune disorders and lung diseases, and are classified as possible human carcinogens (Vatseldutt, 2014). Styrene is classified by IARC as possibly carcinogenic to humans and is shown to cause mammary gland tumors in animal studies. It also acts as an endocrine disrupter (Gray et al., 2009). BPA has been linked with premature birth, intrauterine growth retardation, preeclampsia and still birth (Benachour et al., 2009). It has also been noted that prolonged exposure to BPA shows a significant effect on the sex hormones (progesterone) in females (Wang et al., 2011).

Biodegradation is the process in which microorganisms like fungi and bacteria degrade the natural polymers (lignin, cellulose) and synthetic polymers (polyethylene, polystyrene) (Gu JD et al., 2000a). As the microorganisms possess different characteristics, so the degradation varies from one microorganism to another. Discoloration, phase separation, cracking, erosion and delamination are some of the characteristics which indicate the degradation of polymers. Breakage of bonds, transformation due to chemicals and synthesis of new functional groups are responsible for the variations (Pospisil J et al., 1997).

Problem Statement

The low cost and ease of manufacture have increased global plastic demand more than 150 folds. Tremendous increase in the manufacture and the consumption of plastics including synthetic plastic and natural plastic over recent decades have led to numerous ecological and economic concerns. The persistence of synthetic polymer introduced in the environment by industries, influence major threat to natural ecological systems. Despite recognition of persistent pollution problem posed by plastics, global production of plastics is still at peaks.

The sheer volume of plastics produced each year presents a problem for waste disposal system. The indiscriminate disposal of plastic waste in the environment coupled with inadequate waste management techniques led to various forms of polymer consisting environment nuisance in the ecosystem. With more and more plastic being utilized, environmental problem caused by their non-degradable properties have raised appreciable ecological concern about the increase in production and accumulation of plastic wastes. Therefore, biodegradability of this polymer should be thoroughly understood. Ecological problems connected to the burial of industrial waste claims special attention of processing wastes and recycling of used plastic goods.

Classification of Plastic

According to Their Thermal Properties

Based on their thermal properties they are classified into two types:

Thermoplastic are plastics which can be hardened and softened by repeated heating and cooling process. They are also considered as non-biodegradable plastics. Breaking of double bonds produces thermoplastics. Polyethylene (PE), polypropylene, polystyrene, polyvinyl chloride and polytetrafluoro-ethylenes are examples of thermoplastics.

Thermoset plastics have highly cross-linked structures whereas thermoplastics are linear solids. Here chemical changes involved are irreversible but cannot be recycled. Phenol formaldehyde polyurethanes are examples of thermoset plastics.

According to their Degradability Properties

The chemical properties of plastics can be used as criteria for differentiating them into degradable and non-degradable polymers (Ghosh et al., 2013). Non-biodegradable plastics, usually known as synthetic plastics, are derived from petrochemicals. They have a lot of repetitions of small monomer units; make them a very high molecular weight polymer. In comparison, biodegradable plastics are made from renewable resources that are completely biodegraded in their natural forms, such as components of living plants, animals and algae as source of cellulose, starches, protein and algal materials. They can also be produced by a range of microorganisms (Imre B et al., 2013). Biodegradable plastics usually break down upon interaction with UV, water, enzymes and gradual changes in pH. There are four types of degradable plastics: Photodegradable bioplastics,

compostable bioplastics, bio-based bioplastics and biodegradable bioplastics (Arikan et al., 2014).

Photodegradable Bioplastic has light sensitive groups connected directly into the backbone of the polymer. Ultraviolet Radiation exposure for a long time can disintegrate their polymeric structure, rendering them open to further bacterial degradation. Landfills, however, typically absence of sunlight, thus keeping these plastics non-degraded (Arikan et al., 2014).

Bio-Based Bioplastic are defined as "plastics" in which 100% of the carbon is derived from renewable agricultural and forestry resources, such as corn starch, soybean protein and cellulose.

Compostable Bioplastic is decomposed biologically in a composting process that occurs at a similar rate to other compostable materials, without leaving visible toxic remainders. In order to designate a plastic as bio-compostable, its total biodegradability, its disintegration degree and the possible ecological toxicity of its degraded materials must be determined by standardized tests.

Biodegradable Bioplastic is fully degraded by microorganisms, without leaving visible toxic remainders. The term "biodegradable" refers to materials that can disintegrate or break down naturally into biogases and biomass (mostly carbon dioxide and water) as a result of being exposed to a microbial environment and humidity (Jain et al., 2010). Polyhydroxyalkanoic acids (PHAs) are a significant type of biodegradable plastics, since they possess properties similar to conventional plastics. They are completely biodegradable but may be melted and modeled, making them ideal for use in consumer products.

Plastic Biodegradation by Microorganisms

Microorganisms are able attach to a polymers surface, as long as the latter is hydrophilic. Once the organism is attached to the surface, it is able to grow using the polymer as its carbon source. In the primary degradation stage, the extracellular enzymes secreted by the organism cause the main chain to cleave, leading to the formation of low-molecular weight fragments, like oligomers, dimers or monomers. These low molecular weight compounds are further used by the microbes as carbon and energy sources. Small oligomers may also diffuse into the organism and get assimilated in its internal environment. (Premraj et al., 2005).

Many studies have demonstrated the potential of microorganisms including bacteria and fungi capable of producing exoenzymes and their products under stress conditions, effectively degrades biodegradable polymers (Ahmed, 2018). Several mechanisms have been adopted by the microorganisms for the breakdown of high molecular weight plastics including either the exploitation of microplastics for the fulfillment of their nutritional requirements by microbes or the action of microbial enzymes indirectly (Ahmed, 2018). The ubiquitous strains of bacteria and fungi for degradation of plastic includes *Pseudomonas fluorescence*, *P. aeruginosa and Penicillium simplicissimum* (Ahmed, 2018; Singh et al., 2008; Raziyafatima et al., 2016).

Number of fungi was isolated from the surface of polyester PU foam, using it as a sole carbon source. These fungi isolates were identified and found to belong from the genera *Emericella*, *Trichoderma*, *Aspergillus*, *Fusarium*, *Gliocladium* and *Penicillium* (Bentham et al., 1987). *Geomyces pannorum* was found to be the predominant fungi consisting 22–100 % of the polyester PU degrading fungi (Barratt SR., 2003). The other genera of the fungi including the majority of the organisms found in soil for the degradation of polyurethane like *Plectosphaerella*, *Nectria*, *Neonectria*, *Phoma* and *Alternaria*. The reported biodegradation activity with *Aspergillus niger* was observed to be quite slow with visible signs of deterioration occurring only after 30 days (Russell JR., 2011).

However, certain enzymes e.g. esterases, lipases, and cutinases have the striking ability of hydrolysis of polymers (Wilkes et al., 2017) such as poly ethylene adipate (PEA) and poly caprolactone (PCL) (Ahmed, 2018). The sources of enzymes such as esterases and lipases are fungal species i.e. *Rhizopus delemar*, *R. arrhizus*, *Achromobactor* sp. and *Candida cylindracea* (Ahmed, 2018; Jin et al., 2000; Lam et al., 2008). The growth of many fungi can also cause small scale swelling and bursting, as the fungi penetrate the polymer solids. In recent years fungal strains have been reported for plastic degradation such as *Aspergillus versicolar* (Pramila et al., 2011), *Aspergillus flavus* (Pramila et al., 2011), *Chaetomium* spp (Sowmya et al., 2012) *Mucor circinellodies* species etc. The polythene bags were degraded by some fungal species identified such as *Aspergillus niger*, *A. ornatus*, *A. nidulans*, *A. cremeus*, *A. flavus*, *A. candidus* and *A. glaucus* were the predominant species. List of microorganism used in plastic degradation is mentioned in Table 1.

Table: 1. List of Bacteria Used for Plastic Degradation

Type of Plastic Used	Microorganism	Reference
Polyurethane	*Pseudomonas cepacia*, *Pseudomonas* sp., and *Arthrobacter globiformis*	El Sayed et al., (1996)
LDPE	*Rhodococcus ruber* C208	Chandra and Rustgi (1997)
Polyurethane	*Bacillus* sp.	Blake and Howard (1998)
PVC powder	*Pseudomonas aeruginosa*	Peciulyte (2002)
Degradable polyethylene	*Rhodococcus rhodocorrous* ATCC 29672 and *Nocardia steroids* GK 911	Bonhomme et al., (2003)
Polyethylene bags and plastic cups	*Streptococcus* sp., *Staphylococcus* sp., *Micrococcus* sp., *Moraxella* sp., and *Pseudomonas* sp.	Kathiresan (2003)
LDPE	*Pseudomonas stutzeri*	Sharma and Sharma (2004)
LDPE	*Brevibacillus borstelensis* 707	Hadad et al. (2005)
LDPE	*Rhodococcus ruber* C208	Sivan et al., (2006)
Degradable polyethylene	*Bacillus mycoides*	Seneviratne et al., (2006)
HDPE and LDPE	*Bacillus* sp., *Micrococcus* sp., *Listeria* sp., and *Vibrio* sp	Kumar et al., (2007)
Polyethylene carry bags	*Bacillus cereus*, *Pseudomonas* sp.	Aswale and Ade (2008)

Type of Plastic Used	Microorganism	Reference
Polyethylene carry bags and cups	*Bacillus* sp., *Staphylococcus* sp., *Streptococcus* sp., *Diplococcus* sp., *Micrococcus* sp., *Pseudomonas* sp., and *Moraxella* sp.	Reddy (2008)
Polyethylene carry bags	*Serratia marcescens*	Aswale and Ade (2009)
HDPE, LDPE, and LLDPE	*Rhodococcus rhodochorus* ATCC 29672	Fontanella et al., (2009)
Natural and synthetic polyethylene	*Pseudomonas* sp. (P1, P2, and P3)	Nanda et al., (2010)
Polyethylene carry bags	*Serratia marcescens* 724, *Bacillus cereus*, *Pseudomonas aeruginosa*, *Streptococcus aureus* (B324) and *Micrococcus lylae* (B429)	Aswale (2010)
HDPE	*Arthrobacter* sp. and *Pseudomonas* sp.	Balasubramanian et al., (2010)
LDPE	*Staphylococcus epidermis*	Chatterjee et al., (2010)
Polyethylene bags	*Pseudomonas aeruginosa*, *Pseudomonas putida*, and *Bacillus subtilis*	Nwachukwu et al., (2010)
LDPE	*Bacillus cereus* C1	Suresh et al., (2011)
LDPE powder	*Pseudomonas* sp., *Staphylococcus* sp., and *Bacillus* sp.	Usha et al., (2011)
Degradable plastic	*Pseudomonas* sp., *Bacillus subtilis*, *staphylococcus aureus*, *Streptococcus lactis*, *Proteus vulgaris*, and *Micrococcus luteus*	Priyanka and Archana (2011)
LDPE and LLDPE	*Bacillus cereus*, *Bacillus, Bacillus subtilis*, and *Brevibacillus*	borstelensis Abrusci et al., (2011)
LDPE	*Pseudomonas aeruginosa* PAO1 (ATCC 15729), *Pseudomonas aeruginosa* (ATCC 15692), *Pseudomonas putida* (KT2440 ATCC 47054), and *Pseudomonas syringae* (DC3000 ATCC 10862)	Kyaw et al., (2012)
Polycaprolactone(PCL)	*Aspergillus flavus*	Tokiwa et al., (2009)
Polyhydroxybutyrate(PHB)	*Penicillium funiculosum*	Tokiwa et al., (2009)
PCL	*Aspergillus niger*	Tokiwa et al., (2009)
PHB, PCL	*Streptomyces*	Tokiwa et al., (2009)
Polylactic Acid(PLA)	*Amycolaptosis* sp.	Shimao et al., (2001)
Polyethylene	*Phanerochaete chrysosporium*	Shimao et al., (2001)
Polyurethane	*Pestalotiopsis microspora*	Russel et al.. (2001)
Polyhydroxyalkanoate(PHA)	*Pseudomonas stutzeri*	Shimao et al., (2001)
Polyethylene Adipate (PEA)	*Rhizopus arrizus*	Tokiwa et al., (2009)

In past years polyethylene degrading bacteria has been reported such as *Acinetobacter baumannii*, *Arthrobacter* spp., *Viscosus* spp., *Pseudomonas* spp., *Arthrobacter viscosus*, *Bacillus amyloliquefaciens*, *Thuringiensis Mycoides*, *Cereus pumilus*, *Staphylococcus cohnii*, *Xylosus* spp., *Pseudomonas fluorescens*, *Rahnella aquatills*, *Micrococcus luteus*, *Lylae*, *Paenibacillus macerans*, *Flavobacterium* spp., *Delftia acidovorans*, *Ralstonia* spp., *Rhodococcus erythropolis*, *Pseudomonas aeruginosa* (Kounty *et al.,* 2009) and *Bacillus brevies* (Watanabe et al., 2009).

The microbial species that identified from the sample polythene bags tested were *Bacillus* sp., *Staphylococcus* sp., *Streptococcus* sp., *Diplococcus* sp., *Micrococcus* sp., *Pseudomonas* sp. and *Moraxella* sp. The microbial species are associated with the degrading materials were identified as bacterial genus like *Pseudomonas*, *Streptococcus*, *Staphylococcus*, *Micrococcus*, *Moraxella* (Raziyafatima et al., 2016). In addition to these strains, a thermophilic bacterium, *Bacillus brevis*, with PLA-degrading properties has been isolated from soil.

Tokiwa et al., (2009) proof that fungal species of *Aspergillus flavus*, *Aspergillus niger*, *Penicillium funiculosum* and *Streptomyces* can degrade various kind of plastics. In addition, bacteria that has been stated were *Rhizopus delemar*, *Firmicutes* and *Rhizopus arrizus*. Other scholar shimao et al., (2001) clarified *Fusarium, Amycolaptosis* sp and *Phanerochaete chrysosporium* as fungal species and *Pseudomonas stutzeri* as bacteria species to degrade respective plastic type. Russel et al., (2001) found out single species of fungi *Pestalotiopsis microspore* successfully degrade polyethylene.

Conclusion

Biodegradation process is very eco-friendly. Microorganisms have been found to be able to degrade many pollutants that cause waste management problems. The growth of the microbes responsible for biodegradation must be optimized by controlling the temperature, humidity and incubation time. A basic understanding of the biological processes leading to biochemical degradation will advance the development of new bioremediation techniques. Many Fungal genera such as *Aspergillus flavus*, *Aspergillus niger*, *Penicillium funiculosum*, *Streptomyces*, *Fusarium, Amycolaptosis* sp and *Phanerochaete chrysosporium* and bacterial genera such as *Acinetobacter baumannii*, *Arthrobacter* spp., *Viscosus* spp., *Pseudomonas* spp., *Arthrobacter viscosus*, *Bacillus amyloliquefaciens*, *Thuringiensis Mycoides*, *Cereus pumilus*, *Staphylococcus cohnii*, *Xylosus* spp., *Pseudomonas fluorescens* and *Rahnella aquatills* have been reported to degrade various kinds of plastics such as HDPE, LDPE, Polylactic Acid(PLA), Polyethylene Adipate (PEA), Polyurethane etc. Biodegradation of plastic promises a reduction in plastic waste in future.

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References

Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A. A., Noman, M., & Muhammad, S. (2018). Biodegradation of plastics: current scenario and future prospects for environmental safety. *Environmental Science and Pollution Research*, *25*(8), 7287-7298.

Arutchelvi, J., Sudhakar, M., Arkatkar, A., Doble, M., Bhandari, S., & Uppara, PV. (2008). Biodegradation of Polyethylene and Polypropylene. Indian J Biotechnol 7, 9-22.

Aswale, P. (2010). Studies on bio-degradation of polythene. PhD thesis. Aurangabad, India: Dr Babasaheb Ambedkar Marathwada University.

Barratt, S. R., Ennos, A. R., Greenhalgh, M., Robson, G. D., & Handley, P. S. (2003). Fungi are the predominant micro-organisms responsible for degradation of soil-buried polyester polyurethane over a range of soil water holding capacities. *Journal of applied microbiology*, *95*(1), 78-85.

Benachour, N., & Aris, A. (2009). Toxic effects of low doses of Bisphenol-A on human placental cells. *Toxicology and applied pharmacology*, *241*(3), 322-328.

Bentham, RH., Morton, LHG., Allen, NG. (1987). Rapid assessment of the microbial deterioration of polyurethanes. Int Biodeterior 23, 377–386.

Bonhomme, S., Cuer, A., Delort, A. M., Lemaire, J., Sancelme, M., & Scott, G. (2003). Environmental biodegradation of polyethylene. *Polymer degradation and Stability*, *81*(3), 441-452.

Ghosh, S. K., Pal, S., & Ray, S. (2013). Study of microbes having potentiality for biodegradation of plastics. *Environmental Science and Pollution Research*, *20*(7), 4339-4355.

Gray, J., Evans, N., Taylor, B., Rizzo, J., & Walker, M. (2009). State of the evidence: the connection between breast cancer and the environment. *International journal of occupational and environmental health*, *15*(1), 43-78.

Gu, J. D., Ford, T. E., Mitton, D. B., & Mitchell, R. (2000). Microbial corrosion of metals. *The Uhlig Corrosion Handbook. 2nd Edition. New York: Wiley*, 915-27.

Hadad, D., Geresh, S., & Sivan, A. (2005). Biodegradation of polyethylene by the thermophilic bacterium Brevibacillus borstelensis. *Journal of applied microbiology*, *98*(5), 1093-1100.

Jain, R., Kosta, S., & Tiwari, A. (2010). Polyhydroxyalkanoates: a way to sustainable development of bioplastics. *Chronicles of Young Scientists*, *1*(3), 10-10.

Jin, H. J., Lee, B. Y., Kim, M. N., & Yoon, J. S. (2000). Thermal and mechanical properties of mandelic acid-copolymerized poly (butylene succinate) and poly (ethylene adipate). *Journal of Polymer Science Part B: Polymer Physics*, *38*(11), 1504-1511.

Kathiresan, K. (2003). Polythene and plastics-degrading microbes from the mangrove soil. *Revista de biologia tropical*, *51*(3-4), 629-633.

Koutny, M., Lemaire, J., & Delort, A. M. (2006). Biodegradation of polyethylene films with prooxidant additives. *Chemosphere*, *64*(8), 1243-1252.

Kumar, S., Das, M. P., Rebecca, L. J., & Sharmila, S. (2013). Isolation and identification of LDPE degrading fungi from municipal solid waste. *Journal of Chemical and Pharmaceutical Research*, *5*(3), 78-81.

Kyaw, B. M., Champakalakshmi, R., Sakharkar, M. K., Lim, C. S., & Sakharkar, K. R. (2012). Biodegradation of low density polythene (LDPE) by Pseudomonas species. *Indian journal of microbiology*, *52*(3), 411-419. DOI 10.1007/s12088-012-0250-6

Lam, C. X., Hutmacher, D. W., Schantz, J. T., Woodruff, M. A., & Teoh, S. H. (2009). Evaluation of polycaprolactone scaffold degradation for 6 months in vitro and in vivo. *Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials*, *90*(3), 906-919.

Pilz, H., Brandt, B., & Fehringer, R. (2010). The impact of plastics on life cycle energy consumption and greenhouse gas emissions in Europe. *Summary report June*.

Pospíšil, J., & Nešpůrek, S. (1997, April). Highlights in chemistry and physics of polymer stabilization. In *Macromolecular Symposia* (Vol. 115, No. 1, pp. 143-163). Basel: Hüthig & Wepf Verlag.

Pramila, R., & Ramesh, K. V. (2011). Biodegradation of low density polyethylene (LDPE) by fungi isolated from marine water a SEM analysis. *African Journal of Microbiology Research*, *5*(28), 5013-5018.

Priyanka, N., & Archana, T. (2011). Biodegradability of polythene and plastic by the help of microorganism: a way for brighter future. *J Environ Anal Toxicol*, *1*(4), 1000111.

Raziyafathima, M., Praseetha, P. K., & Rimal Isaac, R. S. (2016). Microbial degradation of plastic waste: a review. *Chemical and Biological Sciences*, *4*, 231-42.

Russell, J. R., Huang, J., Anand, P., Kucera, K., Sandoval, A. G., Dantzler, K. W., ... & Strobel, S. A. (2011). Biodegradation of polyester polyurethane by endophytic fungi. *Applied and environmental microbiology*, *77*(17), 6076-6084.

Shah, A. A. (2007). *Role of microorganisms in biodegradation of plastics* (Doctoral dissertation, Quaid-i-Azam University Islamabad, Pakistan).

Sharma, A., & Sharma, A. (2004). Degradation assessment of low density polythene (LDP) and polythene (PP) by an indigenous isolate of Pseudomonas stutzeri.

Shimao, M. (2001). Biodegradation of plastics. *Current opinion in biotechnology*, *12*(3), 242-247.

Sowmya, H. V., Ramalingappa, M., & Krishnappa, M. (2012). Degradation of polyethylene by Chaetomium sp. and Aspergillus flavus. *Int. J. Recent Sci. Res*, *3*(513), e517.

Strong, A. B. (2006). Plastics: materials and processing 3rd ed. Pearson Prentice Hall, Upper Saddle River, NJ.

Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of plastics. *International journal of molecular sciences*, *10*(9), 3722-3742.

Usha, R., Sangeetha, T., & Palaniswamy, M. (2011). Screening of polyethylene degrading microorganisms from garbage soil. *Libyan Agric Res Cent J Int*, *2*(4), 200-4.

Vatseldutt, S. A. (2004). Isolation and characterization of polythene degrading bacteria from polythene dumped garbage. *Biotechnol Lett*, *53*, 1181-1189.

Watanabe, T., Ohtake, Y., Asabe, H., Murakami, N., & Furukawa, M. (2009). Biodegradability and degrading microbes of low-density polyethylene. *Journal of applied polymer science*, *111*(1), 551-559.

Wilkes, R. A., & Aristilde, L. (2017). Degradation and metabolism of synthetic plastics and associated products by Pseudomonas sp.: capabilities and challenges. *Journal of applied microbiology*, *123*(3), 582-593.